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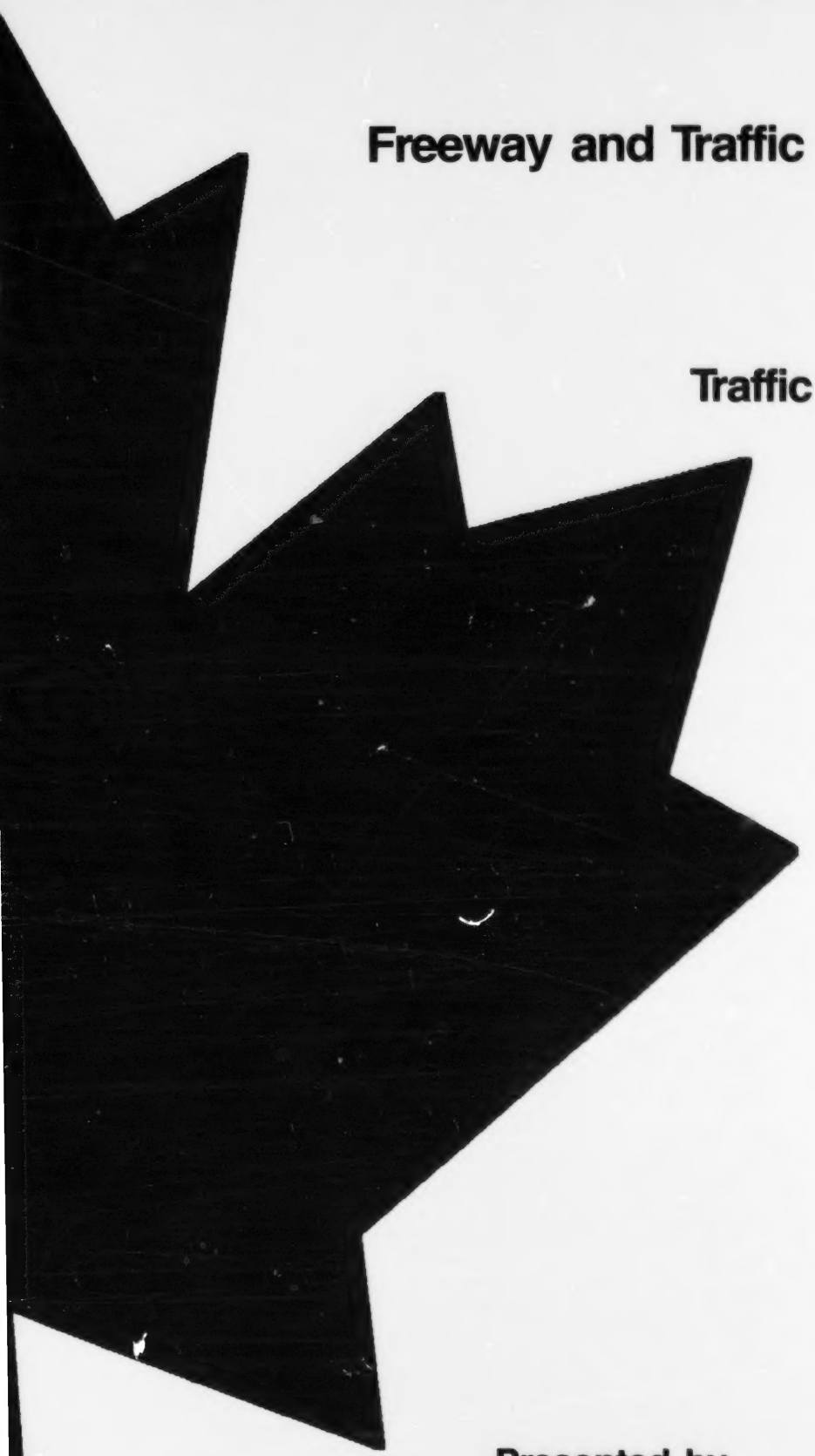
Freeway and Traffic Management

Traffic Control



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Freeway and Traffic Management

Traffic Control

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1/ INTRODUCTION

Cities, developed to enhance the exchange of goods and information among their populace, have had to contend with problems associated with congested roadways and frustrated travellers since the earliest times.

"High mountains are a feeling, but the hum of human cities torture," Byron stated. Many agree with that sentiment, particularly during their daily battle on congested city roads.

The first reaction to recurring congestion has traditionally been to build roads, then to widen them, improve them, and then to widen them once more. With the maturing of our urban centres and, more recently, with financial and social constraints placed on city planners and engineers, other means have had to be found to keep up with growing traffic demand.

Where demand regularly exceeds roadway capacity, the effectiveness of the transportation system suffers. Pollution and fuel consumption increase, public transit and emergency vehicles are unable to function efficiently, and the cost of doing business generally escalates. The growth of our urban centres is, in effect, limited by our ability to gain ready access to vital centres of business and industry.

With the passage of time, our cities have grown, traffic to be handled has increased, and our willingness to accept impediments to free movement has diminished. A number of tools are available to engineers, planners, and administrators to minimize the detrimental effects of urban growth on transportation. Roadway capacity can be increased through the addition of roads or their widening, travel may be restricted or redistributed in time or space, or traffic control measures may be introduced to maximize the capacity afforded by the existing infrastructure.

Traffic control measures include improved signing, the introduction of one-way road systems, parking restrictions, and various active control schemes. These schemes range from the use of stop signs, yield signs, and traffic signals to the implementation of area traffic control systems.

Modern traffic signal control systems offer the transportation professional the most effective tool yet to maximize existing roadway capacity at reasonable cost. Such systems co-ordinate the operation of traffic signals, reduce stops and delays, monitor the operation of traffic signal equipment, track traffic demand and system effectiveness, and generally allow large metropolitan traffic corridors to be managed effectively.

The quantitative benefits of centralized traffic control systems have been repeatedly proven to return the capital cost of their installation within one to two years. The cost effectiveness of modern traffic control systems has therefore prompted most major cities in the world, and many small- to medium-sized ones as well, to adopt electronic rather than civil construction solutions to their traffic problems.

This paper examines, at some depth, isolated intersections, arterials, and the elements of urban traffic control systems, including costs, benefits, and operational and maintenance considerations, and describes Ontario's experience with the development, implementation, and operation of such systems.

2/ ISOLATED INTERSECTIONS

"Crossroads are an enemy to traffic," wrote Le Corbusier, the visionary French architect and planner of the 1920s. The first problem of traffic control is the safe and efficient operation of intersecting roadways.

Although the use of traffic control devices first comes to mind when the control of intersections become necessary, simpler measures have been in use for some time.

Rules of the road were introduced with the emergence of the first intersecting roadways. Reliance on right-of-way rules alone is still appropriate where traffic is relatively light, and it is the means of allocating right-of-way at intersections where no other forms of control are warranted.

As traffic volumes increase, more positive control measures, such as yield or stop signs, are required. Where two high-volume roads

intersect, traffic signals may be warranted. The traffic engineering community recognizes that the imposition of restrictive forms of control, such as stop signs and traffic signals, in many cases, increases traffic delay but may be necessitated by safety considerations.

2.1/ Traffic Signal Warrants

The practice of justifying the installation of traffic control devices through the application of traffic signal warrants helps to prevent an uncontrolled growth of these devices at the expense of increased vehicular delays.

Figures 1 to 3 illustrate the traffic signal warrants of the Ontario Ministry of Transportation and Communications (MTC). Warrants to justify the installation of signals may be based on traffic volumes, traffic delays, pedestrian volumes, or accident rates. Warrants provide the traffic engineer with an objective measure to justify the need for traffic signal installation, but are just as often used to prevent unnecessary installations, often initiated by unjustified public demand.

Stop signs particularly are viewed by the public as appropriate tools to both slow traffic and to discourage the use of residential streets by automobiles. The cost of such inappropriate uses of traffic control devices is significant.

2.2/ Performance Measures

The objectives of traffic control are to improve the safety and efficiency of traffic within the road network. Secondary objectives are the minimization of noise and air pollution generated by vehicles.

The measurement of safety through accident records and noise and pollution levels through standard measurement techniques is relatively straightforward. The elements of traffic system efficiency are varied and more difficult to obtain and quantify. Generally, factors of importance are travel time, vehicular delay, stops, and fuel consumption. In North America, a concern in recent years has been to minimize fuel consumption. Fuel consumption is directly related to stops, delays, and

travel time, and hence, these three factors are normally the subject of study when the efficiency of traffic systems and their operation are evaluated.

Traffic studies are expensive, time-consuming, and require a large number of staff for field data gathering. For this reason, it is preferable, where possible, to make use of reliable historical data and simulation studies to estimate the impact of implementing traffic control measures.

The Ontario Ministry of Transportation and Communications report "Traffic Management Measures to Reduce Energy Consumption" [1] contains information to enable the effects of various traffic control schemes to be estimated with a minimum of field measurement being carried out.

2.3/ Intersection Capacity

The capacity of a traffic facility is the measure of its ability to accommodate a stream of moving vehicles. It is a rate rather than a quantity. The maximum capacity of a facility can be affected by a number of factors, including the roadway geometrics, vehicle performance characteristics, operational controls, and environmental elements.

The number of vehicles that pass a particular point on a facility is determined not only by the capacity of that system, but also by the capabilities of other portions of the system which "meter" traffic to and from the section and by the demand for service that may or may not be present. The amount of traffic that can pass through a signal-controlled intersection from a given approach depends on the green time available to traffic. Therefore, the capacity of an approach to traffic signals depends on the maximum sustainable rate at which vehicles can depart (saturation flow) and the proportion of the cycle time which is effectively green for that movement, as shown in the following formula:

$$Q = S\ (g/c)$$

where
Q = capacity
S = saturation flow

g = effective green time
c = cycle length

When the green period commences, vehicles take some time to start and accelerate to normal running speed, but after a few seconds, the queue discharges at a more or less constant rate called the saturation flow. As defined by Webster [2], "saturation flow is the flow which would be obtained if there was a continuous queue of vehicles and they were given 100% green time."

Though the direct measure of saturation flow is desirable in order to obtain the most reliable results, this is not always practical or possible. Several agencies have studied saturation flows and have summarized their results in tabular form. For example, Webster and Cobbe [3] based their saturation flow calculations on the width of the approach under investigation. In 1966, based on Miller's [4] work, the Australian Road Research Board (ARRB) found that the most important single parameter to be considered when estimating saturation flows was the number and type of lanes on an approach.

Studies conducted by Metro Toronto Roads and Traffic [5] have shown that the ARRB method most closely reflects the Toronto situation and is considered to be the framework for the soon-to-be-published Canadian Intersection Capacity Guide.

2.4/ Signal Timing

Once the need for a traffic signal has been identified, verified, and the signal installed, it is important that the operation of that signal properly reflects on-street requirements. As identified in the MTC Traffic Control Signal Timing Manual [6], improperly operated signals may reduce traffic movement efficiency by

- increasing the frequency and severity of some types of accidents,
- reducing the traffic-handling capability of an intersection,
- producing excessive intersection delay and unnecessary stops (which is not fuel-efficient), and
- encouraging disobedience to signal indicators.

Therefore, the objective of good signal timing is to minimize average delay to all vehicles and pedestrians, total delay to any single group of vehicles and pedestrians, and the possibility of accident-producing conflicts.

As discussed in Sections 2.5 and 2.6, signals are classified by their operating function as either fixed-time or traffic-actuated (semi- or fully) signals. The discussion that follows deals strictly with the former, where the signal is set to repeat a given sequence of signal indications, regularly allotting a fixed amount of time to each phase.

The most widely accepted method for determining cycle lengths and splits for fixed-time signals is the Webster method, which was introduced by the British Road Research Laboratory [2]. Webster stipulated that a fully utilized green phase for an approach can be considered to consist of an effective green period during which saturation flow occurs and a lost time during which no flow takes place.

To calculate the optimum cycle length for overall intersection delay (see Figure 4), Webster proposed the following equation:

$$Co = \frac{1.5\ L + 5}{1 - Y}$$

where

Co = optimum cycle length
L = sum of lost time "l" over the phases
Y = sum of "y" values over the phases
"l" = lost time during phase when no flow takes place
"y" = critical volume/saturation flow ratio for each phase

The optimum effective green times to give the least overall delay to all traffic using an intersection may be calculated by equating the ratio of effective green times to the ratio of the critical "y" values (volume/saturation flow ratio):

$$g^1/g^2 = y^1/y^2$$

where

gi = optimum effective green time for the ith phase
yi = volume/saturation flow ratio for the ith phase

This rule can be extended to three or more phase operations.

Once the phase green times have been established, it is necessary to provide a warning and clearance interval, which is typically the amber and all-red intervals which follow each phase green. The warning (or amber) interval should represent the time travelled during an assumed perception and reaction time of 1.0 s plus the time required to physically bring the vehicle to a stop at a uniform rate of deceleration. Following the warning interval, a clearance (or all-red) interval should be provided to allow vehicles to stop in safety. The length of this clearance interval should be sufficient to allow a vehicle which is too close to the intersection to pass through the intersection before the appearance of the conflicting phase green.

2.5/ Fixed-Time Control

Fixed-time traffic controllers provide predetermined amounts of green time to competing traffic movements at intersections on a predetermined periodic basis. The amount of time allocated to individual movements (split) is based on relative approach volumes and roadway capacities. The total time allocated to all movements (cycle length) is a function of the total traffic at an intersection. Generally, the degree of delay experienced by these movements is equalized by the choice of allocated green time.

Where traffic is relatively light, predictable fixed-time controllers may be adequate. Where traffic demand on an approach is near the capacity of that approach, a small increase in traffic can lead to long queues and delays on one approach, while the opposing approach may be relatively congestion free.

2.6/ Actuated Control

To allow a more equitable and efficient allocation of delay and to minimize overall delay at an intersection, traffic-responsive control is desirable at locations where traffic is unpredictable. Traffic-responsive or actuated controllers sense the presence of vehicles approaching a signal and extend the green phase to preset limits. Both the cycle length and splits will, therefore, vary with each cycle to accommodate changing demand, thereby reducing stops and delays.

Actuated controllers offer significant benefits under light traffic conditions as well. If no vehicles are present on an approach, the green indication rests on the last approach served, generally the busier street.

Controllers which respond to sensors on all approaches are called fully actuated controllers. Semi-actuated controllers monitor only the minor movement and are deemed more appropriate where the approach carries relatively little traffic. The minor movement may be a side street or a left-turn lane. Through the judicious use of appropriate traffic control equipment and proper signal timings, the operation of individual intersections may be optimized.

3/ SIGNAL CO-ORDINATION

When considered in isolation, traffic controllers are timed to minimize delays to approaching traffic, assuming that vehicles arrive in a random fashion. Where traffic signals are closely spaced, the arrival rate of vehicles is no longer random, but forms a predictable pattern dependent on timings at adjacent signalized intersections.

The vehicle arrival pattern depends on a number of factors, including distance to the upstream signal, travel speed along the roadway, and the diffusion of the vehicles released from the upstream signal, referred to as platoon dispersion.

In the ideal case, the arrival of vehicles from an adjacent intersection is simply the distance divided by travel speed. Where signals are

closely spaced, actual arrivals may approximate the ideal. With greater signal spacing and increased side friction, the effects of platoon dispersion become more pronounced.

The efficiency of operation of a series of traffic signals may be significantly improved by timing the starts of the green periods (offsets) along an arterial to coincide with the arrival of vehicle platoons from upstream intersections. This imposition of offsets and a common cycle length on a group of signals is referred to as co-ordination.

The resultant green period, along the street under co-ordination, is referred to as a "green band," providing traffic with a series of green signal displays as it moves along the arterial.

It has been demonstrated in numerous studies and field experiments that the co-ordination of signals along moderate to heavily travelled roads is the most cost-effective action available to reduce delays, travel time, fuel consumption, and pollution.

Interconnection and co-ordination of signals, based on a U.S. Department of Transport study and reported in Reference 1, results in approximately 10 to 50 vehicle hours of travel saved per dollar spent.

In Ontario, municipalities are strongly encouraged to undertake signal co-ordination programs to reduce travel delays and cut fuel consumption.

3.1/ Co-ordinated Signal Timing

On a one-way street, the calculation of optimum offsets is handled in a straightforward manner. On a two-way road, the development of offsets that minimize overall traffic delay is more involved.

Figure 5 is a space-time diagram displaying green bands of traffic traversing the arterial. Space-time diagrams may be used to design as well as to display arterial signal timing plans. By varying the cycle length and individual intersection offsets and splits, co-ordination in both directions may be achieved. Manual optimization techniques, such as

space-time diagrams, are tedious, time-consuming, and inexact, because the effects of turning traffic are difficult to take into consideration.

A number of computer-based programs that run on mini- and micro-computers have been developed to assist the traffic engineer to quickly produce signal timings for various anticipated traffic conditions. Maxband and the Signal System Optimization Program (SSTOP) are examples of computer programs that are relatively easy to use and yield effective signal timing plans.

The development of effective timing relies on the availability of up-to-date and accurate counts of vehicular traffic as well as knowledge of intersection geometrics and traffic characteristics. Considerable effort may have to be expended to accumulate, analyse, and code the necessary data to run an optimization program.

Typical arterial signal optimization programs will require the following input data:

- main-street volumes
- side-street volumes
- turning volumes
- signal phasing
- intersection geometrics
- arterial travel speeds
- intersection spacing
- intersection capacity

The output produced by these programs includes cycle lengths, splits, and offsets, which the traffic engineer may use to time his traffic controllers.

Where traffic patterns are changing because of population growth, business development, or street network alterations, updated traffic counts and signal-timing plan upgradings are recommended. In any case, timings should be rechecked a minimum of every two to three years.

3.2/ Timing Plan Selection

Most arterials will experience changing traffic patterns throughout the day and on different days of the week. To be effective, timing plans implemented by the master controllers must match these changing patterns as closely as possible. Where traffic patterns are predictable, timing plans may be called up according to a predetermined time schedule. On arterials, where traffic demand is unpredictable, it may be appropriate to call up traffic plans in response to such demand. This form of control is called traffic-responsive plan selection. Typically, such systems will have a pair of detectors in lanes of opposing traffic, measuring traffic volumes and levels of congestion or occupancy. For accuracy, system detectors need to be placed well upstream of any signals, to prevent queues from backing up over the detector loops.

Depending on relative volumes, the master controller selects the offset to favour either one or both directions of travel. Based on the level of congestion, the masters will select the most appropriate cycle length. The greater the level of congestion, the greater the cycle length selected.

Although it may seem that traffic-responsive control is bound to be more effective than time-of-day control, this is often not the case. It is often difficult to set appropriate levels where timing plans are to change from one plan to the next. Each plan change also disrupts traffic, and too frequent plan changes prevent effective co-ordination of signals.

The need to introduce delays into the plan transition routine to prevent too frequent plan changes may, however, make the system too slow to respond to changes in traffic flow.

For these reasons, it is often advisable to operate co-ordinated systems on a time-of-day basis. A Ministry study conducted a few years ago, "Comparison of Three Arterial Traffic Control Strategies Through Field Measurements" [7], found no significant difference in the effectiveness of time-of-day and traffic-responsive arterial control.

3.3/ Traffic Data Acquisition

The gathering of traffic data is a time-consuming and labour-intensive task. Although arterial traffic volumes may be obtained using electronic counters, turning movement and intersection capacity measurements require the use of field staff with some training.

Typically, traffic data are accumulated in 15 min time intervals. Figure 6 shows a typical field data sheet used by traffic personnel to record traffic movement at an intersection. A number of electronic or micro-processor-based data acquisition units have come on the market recently. When used with appropriate office micro-computers and computer programs, the transfer of field data, their analysis, and reporting can be significantly speeded up.

The Ministry has developed a flexible, inexpensive micro-computer-based traffic-gathering device to assist in carrying out field studies. The unit contains 16K of memory, a full alphanumeric keyboard, and may be connected directly into a printer, a modem, or computer.

3.4/ Traffic Signal Interconnection

The physical connection of signals may be achieved through various means. One method involves the installation of a multi-wire cable connecting a master controller to local controllers at each intersection. By applying a high-voltage ac signal to the lines at each intersection, the master controller issues synchronization pulses and commands the local units to operate at the appropriate offset and cycle length.

Similarly, twisted-pair cable may be used along with communications modems and other necessary electronic interface circuitry at the master and the local controllers to achieve signal co-ordination.

The twisted-pair cable may be owned and installed by the local traffic operating jurisdiction. If it proves economically advantageous, dedicated telephone circuits may also be used, although this is not common practice for smaller arterial signal networks.

A relatively recent development allows signals to be co-ordinated without the need for physical interconnection of the controllers. Co-ordination is achieved through the use of highly accurate digital clocks operating in synchronism in each controller.

Timing plans, consisting of splits, cycle lengths, and offsets, are stored in each controller. Plans are selected by the internal clocks in all the controllers simultaneously, thereby achieving co-ordination. This form of synchronization is referred to as cableless interconnect or time-base co-ordination.

Many controllers sold today offer time-base co-ordination capabilities within the standard control unit. Co-ordination units may also be purchased independently and used to co-ordinate existing controllers.

3.5/ Effectiveness of Various Control Methods

The appropriateness of the control methods discussed earlier depends largely on traffic conditions at the location under consideration.

Table 1 compares energy consumption for four types of intersection control -- two-way yield, two-way stop, four-way stop, and fixed-time traffic signal -- where daily main-street volumes are 8320 vehicles and side-street volumes are 1500. For the given conditions, the two-way yield and two-way stop signs prove most efficient and four-way stop signs least efficient. Although expressed in terms of fuel consumption, the relative amount of fuel consumed by the four control modes is a reflection of the number of stops and amount of delay experienced by traffic under the four control modes.

Figure 7 compares fuel consumption for various modes of control under changing main-street to side-street volumes. At ratios of close to 1, co-ordinated signal operation proves most efficient, while at locations where these ratios are greater than three, flashing yellow/red, the equivalent of a two-way stop, is found to be most effective.

In virtually all cases, four-way stops are most wasteful of time and fuel. Of signalized control methods, fixed-time control proves least efficient.

Formulae provided in Reference 1 permit an evaluation of the performance of a range of control modes for any given set of traffic conditions.

3.6/ Traffic Control Equipment

In the past, fixed-time controllers were most commonly of electromechanical design and limited in capability. Actuated controllers and master controllers for co-ordination tended to be costly, bulky, and unreliable.

The emergence of micro-processor technology has had a significant impact on the traffic control industry. The tendency is to use micro-processors for even the most basic two-phase fixed-time controller. The method of control and the number of phases controlled are defined by the program in the controller rather than in controller hardware. This allows a controller to be operated as a fixed-time or traffic-actuated controller, a master controller, or even a time-based co-ordinated controller, by simply changing the control program within the machine.

The approach of using flexible undedicated micro-processor-based traffic controllers offers significant advantages to operating agencies in terms of procurement, spares, maintenance, and operations.

3.6.1/ The Model 170 Program

In the late 1970s, the Ministry of Transportation and Communications adopted the Model 170 micro-processor-based controller as its standard for all traffic signal control applications.

The Model 170 is a specification for traffic signal control hardware, covering the cabinet, controller, monitor, detector, amplifier, and all other hardware components required for intersection control. The Ontario Traffic Signal Control Equipment Specification [8], now improved through modification for Ontario applications, originated with the Departments of

Transportation for the states of New York and California. The use of a standard user-defined specification offers a number of advantages to operating agencies, along with a few possible drawbacks.

The advantages are those related to standardization, interchangeability, competitive tendering, and flexibility. Any equipment designed and purchased to the Specification is interchangeable with products from other manufacturers. Traffic control programs written for one machine will run in all Model 170s. This eliminates the need to learn to time and operate various models of equipment normally encountered in a municipality using a multitude of equipment. This interchangeability and standardization is achieved without sacrificing competitive tendering.

Although some Model 170 suppliers offer operational software with their equipment, software may also be obtained from government agencies and consultants or developed by operating agencies, thus relieving the equipment supplier from having to have a background in traffic control. This has allowed a number of competent Canadian electronics firms with no previous traffic control background to become suppliers of 170 equipment, not only to Ontario and Canada, but to the United States as well.

The adoption of the Model 170 program may encourage the development of an indigenous traffic control industry in countries with limited industrial experience in the traffic control field.

The cost of Model 170 equipment is competitive with equipment supplied through more traditional channels.

Today, the Ministry is using over 400 Model 170 controllers as fixed-time and actuated intersection controllers, as arterial master controllers, and as time-based co-ordinated controllers.

On freeway traffic management projects, Model 170s will perform all field processing functions, including ramp metering, lane-control handling, and detector-station processing. An optional communications card that is housed within the controllers permits communications over telephone lines and over fibre-optics or coaxial cable, with appropriate modulation equipment.

It should be pointed out that adoption of the Model 170 places an additional burden of responsibility on the operating agency, which becomes the integrator of the software and the various hardware components. It is strongly recommended that agencies that adopt the Model 170 as their standard controller should be prepared to conduct detailed acceptance testing of their equipment and to develop in-house some software development capabilities as well.

A list of Model 170 equipment suppliers may be found in Reference 9.

3.6.2/ Detectors

Inductive loops buried in the pavement are the most common vehicle sensors used in traffic control applications today. The detector loop is connected to sensitive electronic amplifiers which sense the presence of vehicles over a loop, through a change in the loop's inductance.

Loop-detector amplifiers have grown in sophistication over the years, with today's amplifiers able to detect small motorcycles, as well as trucks, under changing environmental conditions.

Critical to long and reliable operation of loops is a careful and supervised installation procedure. Locations experiencing extremes of temperature must take special care to minimize loop breakages caused by pavement heaving and breakup. The Ministry's "General Conditions and Guidelines for the Installation of Traffic Detector Inductance Loop Sensors" [10] provides a practical guide for the installation of inductive loops.

4/ COMPUTERIZED TRAFFIC CONTROL SYSTEMS

As discussed earlier, the interconnection and co-ordination of closely spaced traffic signals produces significant benefits to motorists in terms of reduced travel times and fuel consumption.

Arterial master systems are appropriate where only a limited number of signals or signal systems are to be co-ordinated. With larger systems, it becomes desirable to concentrate the control functions of several local co-ordination systems into a single central controller.

Computerized Traffic Control System (CTCS) is a term used to describe a class of traffic control systems that control all of a municipality's signals from a central location. These systems are the most sophisticated in the hierarchy of traffic control systems, normally comprising a mini-computer and an array of programs for controlling and monitoring traffic signals, a communications network that permits the two-way transfer of information between the central facility and each intersection, and a set of data processing, analysis, and reporting routines that permit optimum management of the traffic signal network.

Most major cities in the world today operate some form of CTCS. In North America alone, approximately 150 such systems are currently in operation. Nine municipalities in Ontario, including Toronto, which introduced computerized control of traffic signals in 1963, now operate or are in the process of installing computer-based systems. The significant growth in the number of cities operating CTCS's in Ontario is to some degree the result of the efforts of the Ontario Ministry of Transportation and Communications (MTC) to encourage Ontario municipalities in this direction.

In 1978, MTC undertook the Municipal Traffic Control System (MTCS) project [11] to examine the feasibility of using computer-based traffic control systems in small- to medium-sized municipalities. After surveying 43 Ontario municipalities and over a dozen traffic control system suppliers, it was concluded that CTCS's were not only appropriate for Ontario municipalities, but that such systems were readily available from a number of suppliers.

The Ministry of Transportation and Communications, along with the Ontario Ministry of Energy and the federal Ministry of Energy, then provided 75% funding for a three-city demonstration of the application of CTCS technology in smaller municipalities. Canadian General Electric became the successful bidder to supply and install three systems in the city of Brantford and the regional municipalities of Waterloo and Durham.

Since the successful completion of the three systems in 1982 another system has been completed, three more are nearing completion, and two cities are in the process of preparing specifications for procurement.

As system costs decline and urban congestion grows, it is safe to estimate that within 10 years, most urban centres with populations exceeding 100 000 will opt to install computer-based traffic control systems.

4.1/ Functional Capabilities

Computerized traffic control systems are characterized by the sophistication of their traffic control algorithms, extensive data storage analysis and reporting capabilities, and ability to monitor and modify the operation of intersection equipment.

These capabilities are made possible by central computer hardware and software and two-way communications provided between the central facility and each intersection. It is the ability to continuously monitor changing traffic conditions and then to take immediate appropriate action that makes CTCS's a powerful traffic engineering tool.

Two-way communications permits a wide range of control strategies to be employed and an unlimited number of different timing plans to be stored and implemented. This is accomplished through the capability of the computer to control each individual intersection on a second-by-second basis. This level of control permits the operator to vary not only the cycle length and offset, but also the green time at each intersection. Whereas arterial co-ordination systems required field entry of local timing parameters, CTCS's make it possible for the system operator working from the computer console to examine and, if necessary, modify these values from the computer console.

This capability encourages system operators to keep timings up to date and also reduces the possibility of erroneous timings being entered at the intersection through previous laborious manual timing procedures.

Systems offered by the more than one dozen established traffic control system suppliers in the world vary in many details. Most, however, offer the features necessary for effective traffic control and reliable operation.

The following are key system requirements contained in the specification used to procure the latest Ontario systems:

System Control

- Adequate number of control areas and timing plans.
- Manual, time-of-day, and traffic-responsive plan selection.
- Centralized special function implementation.
- Central input of controller timing parameters.
- Ability to interface with existing control equipment, both fixed-time and actuated.
- Critical intersection control.

System Maintenance and Operations

- Continuous monitoring of controllers and detectors.
- Map or colour graphics display.
- 24 h unattended operation.
- Automatic restart following power failure.
- Co-ordinated operation upon central computer failure.
- Traffic engineering language.

System Management

- Modular expansibility.
- Failure reports.
- System performance reports.
- Automatic historical data base generation.

In addition to these basic requirements, some systems offer, and some municipalities may require, certain additional features:

- emergency vehicle priority routing
- bus pre-emption
- data processing capability
- remote maintenance terminal
- stand-by power source
- continuing system operation upon disk failure
- automatic signal-timing generation and implementation

As these key functional capabilities are offered by most system suppliers, the procurement of traffic control systems through competitive tendering becomes highly feasible.

Ontario municipalities purchasing CTCS's have made use, after minor modification, of the functional specification developed for the MTCS project. The functional nature of the specification has encouraged most North American suppliers to respond to these tender calls and has helped to keep costs down.

4.2/ Modes of Control

The flexibility and power of traffic control computers permits a variety of traffic control modes to be employed. The four common classifications are the following:

1/ manual
2/ time of day
3/ traffic responsive
4/ real-time control

Most systems tend to operate in the time-of-day mode, by prescheduling the calling of plans to meet predicted daily traffic conditions. Unless traffic is highly variable, time-of-day control is most appropriate for most jurisdictions, particularly in the first few years of a system's operation. It generally takes that long for operators to become totally familiar with their systems and to experiment with traffic-responsive plan selection.

Traffic-responsive control involves the establishment of a matrix of volume and occupancy conditions as measured by system detectors that are associated with particular predefined traffic control plans. The plans, in most cases, are identical to those used under time-of-day control. In the traffic-responsive mode, traffic is continuously monitored. The system then selects the plan that most closely matches current traffic conditions. As with arterial master control systems, care must be exercised to ensure that the system is responsive to changing conditions,

without allowing too frequent plan changes, which could disrupt traffic flow.

Most systems will permit control modes to be selected on a time-of-day basis, thus providing a possible time-of-day override of traffic-responsive operation. This is often desirable to ensure that major traffic conditions, such as morning and evening rush hours, are anticipated rather than reacted to, as traffic-responsive selected plans come into force some 15 to 30 min after the triggering condition occurs.

The ability to select timing plans through manual intervention by the operator is a useful feature. Traffic plans to handle special events, such as parades, sporting events, or disruptive weather conditions, are best called up through manual means. Should road closures caused by accidents or construction occur, the operator may generate new plans or alter existing ones to minimize disruption to traffic.

The three control modes just described make use of stored timing plans generated earlier through various means. The production of timing plans is time-consuming, often requiring considerable staff time to gather traffic volumes, generate the plans, and translate these into appropriate data for the control system.

To overcome the cost and difficulty of manual-timing plan generation, systems have been developed which produce optimum timing plans automatically on an ongoing basis, while controlling traffic. Plans are generated based on currently sensed traffic conditions. The expected measure of performance of the network under the last generated plan is then compared with the performance of the current plan. If the newly generated plan improves traffic performance by reducing stops and delays, it is implemented. Plans may be recalculated every 15 to 30 min. This mode of control is referred to as second-generation control. The chief advantage of such real-time control schemes is that no manual effort is involved in the production of timing plans and that plans are continually and automatically kept up to date.

In practice, second-generation control has not proven to be superior to time-of-day and traffic-responsive control. Real-time plan generation

requires intensive detectorization of the network. The cost of installing and maintaining detectors and the limited benefits to be derived from these systems have curtailed the implementation of second-generation systems.

Part of the problem with second-generation schemes is the 15 to 30 min delay before required traffic plans can be implemented. Third-generation schemes try to overcome this problem by optimizing and implementing timings on a cycle-by-cycle basis. One such system, SCOOT [12], developed by the British Transport and Road Research Laboratory (TRRL), has been tried in a number of British municipalities with encouraging results. Again, the need for heavily detectorizing the street network is a significant deterrent to the general acceptance of SCOOT.

4.3/ Signal-Timing Plan Generation

Effective operation of a co-ordinated network of urban traffic signals requires up-to-date signal timing plans that minimize stops and delay. Because of the large number of signals in a typical network and the large number of intersecting arterials, manual development of timing plans becomes virtually impossible.

A number of signal-timing optimization programs have been developed over the years. TRANSYT, developed by Dennis Robertson of TRRL, has gained widespread worldwide acceptance. Various versions of the program have come into use, with 7F being the most up-to-date version used in North America. TRANSYT-7F provides estimates of fuel consumption in addition to optimizing signal timings based on vehicle stops and delays.

The input requirements of the program include network geometrics, saturation flows, travel speeds, traffic volumes, and signal timing parameters. The program simulates the movement of platoons, incorporating into the simulation effects of signal delay and platoon dispersion. Both intersection splits and offsets are varied to arrive at an optimum set of timings that minimize stops and delays.

The program produces a system performance table, controller timing settings, as well as time-space diagrams of specified paths in the network.

The TRANSYT-7F User's Manual [13] provides a comprehensive description of the package. Numerous studies have shown that TRANSYT is an effective optimization program that produces reliable and readily usable signal timing plans.

A similar optimization program, Signal System Optimization Program (SSTOP), has been developed in Ontario through the co-operative efforts of Metropolitan Toronto, McMaster University, the federal government, and MTC. SSTOP was designed to reduce the significant input requirements of TRANSYT, as well as to reduce computer time and computer resources required to run the program, while retaining the comprehensive output of TRANSYT. SSTOP has been shown (Reference 14) to be comparable to TRANSYT in the timings generated, at a fraction of the cost.

SSTOP, first produced to run on a mainframe computer, has been rewritten to run on an IBM-PC or compatible micro-computers. A typical 30-signal network optimization can be completed on an IBM-PC in approximately 20 min.

The SSTOP program on a diskette, along with a User's Guide [15], may be obtained from the MTC.

4.4/ One-and-One-Half-Generation Control

While computer-based optimization programs such as TRANSYT-7F and SSTOP are of great assistance to the traffic engineer, the amount of manual effort required to produce timing plans and incorporate them into a CTCS's repertoire of available plans inhibits the timely updating and development of timing plans.

With a desire to automate the generation of timing plans without incurring the considerable cost of detectorizing the network to the degree required for second-generation systems, one-and-one-half-generation systems have been developed. One-and-one-half-generation control minimizes the manual effort involved in providing the required input to TRANSYT, SSTOP,

or other optimization programs. It also generates signal timing plans to be used directly by the CTCS, thus eliminating the need to translate optimization program outputs into timing plans for use by the CTCS.

Currently only one North American supplier of CTCS's offers a one-and-one-half-generation option with their system; Canadian General Electric and others are, or will be, expected to develop one-and-one-half-generation systems in the near future.

A one-and-one-half-generation capability will be part of the specification for the next system being implemented in Ontario for the city of Burlington.

4.5/ System Hardware

Figure 8 shows a schematic diagram of the main components of a CTCS.

The central facility houses the computer and its peripherals, central communications, the operator's console, including cathode ray tubes (CRTs) and printers, and usually a map.

Computer equipment functions best when housed in a humidity- and temperature-controlled environment. As computer-related equipment tends to be noisy, it is advisable to house the computer in a room separate from the operating staff.

The computer provided with the system must be of sufficient speed and memory size to meet the operational requirements of the user. Rather than specifying speed, word size, and total memory, it is important to functionally describe the intended operation of the system.

Operational requirements may include the capability to have more than one operator work on the system at any one time, the ability to run general-purpose programs while controlling traffic, or the facility to write programs in various languages. It then becomes the supplier's responsibility to translate these needs into appropriate hardware solutions.

Although, not necessary for system operation, a wall map able to depict the operation of detectors and controllers on the street has proven to be valuable for both engineering and public relations purposes.

As a minimum, the map must be capable of displaying controller status at each intersection and the presence of vehicles at system detector locations. More sophisticated maps will display aggregated data, such as vehicular speeds and volumes.

The current map design specified in Ontario calls for a mosaic-type map composed of up to several hundred 7.6 cm by 7.6 cm (3 in. by 3 in.) replaceable modules. The modularity of the map simplifies the upgrading of the map to reflect changes in signal or road network.

Many suppliers now offer colour graphics displays of both network operation and individual intersection operations on colour monitors. This type of display offers a more detailed view of operations at the intersection and has been found to be a useful and cost-effective display device.

The communication interface and control unit (CICU) at the intersection allows the central facility to communicate with and control the intersection signal controller. The CICU also accepts detector inputs and accumulates detector data before transmission of the data to the central facility.

Intersection controllers normally require modification to accept the CICU and to make available necessary control points within the controller for central control and monitoring.

4.6/ Communications

The communications subsystem provides the link between the central facility and the intersection.

The physical medium may be copper wire, coaxial cable, or fibre-optics cable. Some systems rely on radio for communications, obviating the need for any physical link. The essential feature of all communication

systems employed for CTCS applications is that two-way communications be possible. That is, data must be sent from the central facility to each intersection, as well as from the intersection to the central facility. The communication lines may be installed by the operating agency or leased from the local telephone company or cable TV distributor, depending on financial considerations.

The choice of medium to be used should be based on an in-depth examination of technical factors, as well as the capital, maintenance, and leasing cost of potential alternatives. The Ministry has encouraged Ontario municipalities to evaluate communications costs over the life of a system rather than consider capital costs only. Communications costs over a normal 15-year system life often exceed the capital cost of the rest of the system.

Many telephone companies offer a variety of tariffs depending on the physical configuration of the traffic system communications network. In Ontario a 50 to 70% saving in tariff charges was achieved by routing communications to several closely spaced intersections through a "master" controller acting as a local distribution point.

This star network, combined with the use of one pair of voice grade lines per intersection, has resulted in an approximate annual leasing cost of $100.00 per intersection per year in most medium-sized municipalities.

Two recently installed traffic control systems in Ontario have made use of the local cable TV coaxial network, modified for two-way transmission for communications. The life-cycle cost of the cable network, including the cost of conversion to two-way transmission, was found to be competitive with leased telephone rates. The performance of the system is expected to be superior to that possible using leased telephone lines.

Traffic control systems requiring the transmission of video signals must use coaxial cable or fibre optics, which provide the bandwidth necessary for video transmission.

The communication messages are normally transmitted in digital form. Time division multiplexing (TDM) techniques are used to allow more than

one intersection to be controlled on a single wire pair. Frequency shift keying (FSK) is the most commonly used modulation technique because of its compatibility with voice-grade telephone lines and low cost achieved through high-volume production.

4.7/ Costs and Benefits

It has been widely demonstrated and accepted that the co-ordination and proper timing of traffic signals is a highly cost-effective measure. In terms of fuel savings alone, the capital cost of installing a CTCS is returned in less than two years in most cases.

In addition to reducing fuel consumption, controlling traffic flow and reducing congestion and delay brings about a reduction in air pollution and helps to reduce certain types of traffic accidents.

Historical traffic data gathered automatically by the system are useful not only in keeping signal timings and performance at optimum levels, but also in reducing the need to gather such data manually for traffic as well as planning purposes.

Improvements in traffic flow reduce congestion and queuing at intersections, thereby increasing the storage capacity at the intersection and possibly eliminating or delaying the need to reconstruct the intersection to help alleviate the congestion problem.

Traffic control systems offer a number of non-quantifiable benefits as well. Continuous monitoring of field equipment minimizes the time to respond to field equipment failures.

The ability of traffic engineers to directly control and monitor the operation of traffic signals results in a greater interest being taken in the operation of traffic signals, with resultant improvements in on-street operations.

In many cases, the attention the CTCS draws to the activities of the traffic department and the perceptible benefits the system provides often

allows the department to upgrade outdated field equipment and build up staffing to necessary levels.

The cost of installing and operating a CTCS varies, depending on the communication system used, the type of existing traffic controllers in place, and the amount of work the municipality is willing or able to undertake on its own.

A turnkey system, making use of existing controllers, using leased telephone lines and relying on consultants to engineer and manage procurement, would cost approximately $10 000 per intersection for a system of 200 intersections. The cost per intersection is greater for smaller systems and less for larger systems. These costs reflect North American prices and may vary significantly elsewhere.

The cost of a municipally owned communications network adds considerably to the cost quoted and depends on the installation method used.

The cost of maintaining the CTCS after installation is normally not significantly greater than maintenance of the replaced system. Normally a maintenance contract is drawn up with the supplier of the central computer to service and maintain the computer and its peripherals. Field equipment may be maintained by the municipality through traditional means.

An already well-run operation will normally require one additional staff member to operate the system and carry out related traffic engineering tasks.

The system user may encounter one additional cost: the leasing of communication lines. Such costs are highly variable, depending on the local tariff rates, the configuration of the communication system, and the physical dimensions of the network. Within Ontario, leasing costs vary between $100 and $1000 per intersection per year.

A municipality is strongly encouraged to investigate communication options and costs in the earliest stages of an implementation, to ensure that the most cost-effective communication system is specified.

4.8/ Procurement

Procurement means the establishment of system requirements, the preparation of specifications, award of tender, and the installation and commissioning of the system.

A number of approaches exist for potentially successful system implementation. Some already tried methods include hiring of a systems house to design a unique package of hardware and software; the selection of a particular system through negotiations with the supplier; the preparation of detailed hardware and software specifications, followed by competitive tendering; in-house system development; and the preparation of functional specifications and award following tendering.

Each approach has its merits and difficulties. Ontario municipalities have adopted the functional specification route, with generally successful results. This approach was chosen as it ensures the widest participation from suppliers, competitive pricing, maximum use of off-the-shelf proven technology, and minimum risk.

Most municipalities initiate the procurement process by carrying out a feasibility study to determine the following:

- cost/benefit of the system
- life-cycle cost of various communication options
- size and extent of the system
- system functional requirements
- extent of field modifications
- number of controllers to be replaced
- method of award and implementation

The 12 Ontario municipalities that embarked on CTCS projects in the last eight years have hired consultants to carry out their feasibility studies and provide ongoing technical and management support during system implementation. The Ontario consulting firm of DeLCan Ltd. has provided the consulting services for most of these projects, as well as for a number of major projects outside Ontario.

The feasibility study and the establishment of system requirements is followed by the preparation of specifications. The Ontario Ministry of Transportation and Communications recommended, and municipalities have accepted, the use of detailed functional specifications as the procurement vehicle. The specification first prepared under the MTCS umbrella and used to procure the first four systems in 1980 has been improved and enhanced for each subsequent system, while maintaining its functional nature.

The use of functional specifications necessitates the adoption of a two-stage bid and award process. Interested suppliers are required to first submit a technical proposal detailing their compliance with the specification. In addition, certain information detailing the company's financial and management resources is also asked for.

Following a detailed review of all proposals and an interview with suppliers, the technical proposals are either accepted, accepted with modification, or rejected. Suppliers receiving approval are then invited to submit costed bids with the lowest cost system generally being chosen.

In cases where the communications network proposed by suppliers can have a significant impact on ongoing operation costs, a life-cycle cost formula may be applied to the costs provided by suppliers. In at least one instance the lowest price proved to have the highest life-cycle cost and was rejected. The use of life-cycle costing is strongly recommended where ongoing operations and maintenance costs vary between proposed systems.

To ensure fairness to all, the method of evaluation of bids must be stated clearly at the proposal request stage.

Implementation brings with it a variety of problems related to specification interpretation, schedule adherence, and innumerable day-to-day technical and administration questions.

The day-to-day supervision of the implementation phase of projects requires both technical and managerial expertise, as well as considerable time. Unless both these commodities are available to the procuring

agency, a consultant needs to be hired. The cost of such consulting services typically ranges between 15 and 20% of the cost of the system.

The final phase of implementation includes acceptance testing of all system functions and components, followed by an observation period of three to four months, during which time the city operates the system and reports on problems encountered.

Final system acceptance comes after successful completion of the observation period. A warranty period of one to two years may follow this period, with the suppliers held responsible for any hardware or software problems encountered.

A well-written specification and continual monitoring of the progress of the work helps to minimize unpleasant surprises at the approach of the contract completion date and helps to keep the project on schedule.

Both parties to the contract, however, need to be ready to make occasional compromises in the interest of all concerned. The consultant needs to assume the role of conciliator in some cases.

4.9/ The Ontario Experience

In the last five years, Ontario has seen the development of a vital traffic control systems industry, as well as the implementation of almost a dozen systems.

This development has come about through the co-operative efforts of Ontario municipalities, industry, the consulting community, and the Ontario government.

Municipalities identified the need for improved operation of their traffic signal network. Traffic engineering staff in the municipalities recognized the opportunities offered by the application of computer and communications technology to their traffic problems and accepted the risks associated with embarking on a new course. The procurement and implementation of the systems required considerable extra effort on the

part of municipal staff to learn how to apply new techniques as well as to carry out the necessary related office and field work.

Municipalities which took an active part in the implementation of their systems ultimately derived the greatest benefits once the systems become operational. Their familiarity with every facet of the system allowed them to understand and utilize their systems to their full potential.

Ontario consultants and traffic control equipment suppliers recognized an opportunity to participate in a vital and growing segment of the traffic control market and made the decision to commit staff resources to its support. DeLCan Engineers and Planners, Canadian General Electric, and Guild Electric proved most successful in providing the necessary systems and services, which resulted in many successful systems. The Ministry of Transportation and Communications acted as a catalyst in the effort by bringing together municipalities, consultants, and suppliers in a focused effort to help solve the traffic problems of which the municipalities were already aware. MTC also provided technical and financial assistance to speed the process along.

Now that the benefits, requirements, and means of implementation of systems have been well established, the effort is shifting to making better use of the systems in place and to making use of the systems simpler and more efficient.

Once again, the co-operation of municipalities, the Ministry, consultants, and industry are being mustered for the common benefit of all.

5/ REFERENCES

[1] "Traffic Management Measures to Reduce Fuel Consumption," Ontario Ministry of Transportation and Communications, November 1981.

[2] Webster, F.V., "Traffic Signal Settings," British Road Research Laboratory Technical Paper No. 39, Her Majesty's Stationery Office, London, 1958.

[3] Webster, F.V. and Cobbe, B.M., "Traffic Signals," British Road Research Labor- atory Technical Paper No. 56, Her Majesty's Stationery Office, London, 1966.

[4] Miller, A.J. et al, "Australian Road Capacity Guide -- Provisional Introduction and Signalized Intersections," Australian Road Research Board, Bulletin No. 4, June 1968.

[5] Rach, L. et al, "Improved Operation of Urban Transportation Systems -- Volume 1 -- Traffic Signal Control Strategies -- A State-of-the-Art," Metropolitan Toronto Roads and Traffic Department, March 1974.

[6] Karnig, B. et al, "Traffic Control Signal Timing and Capacity Analysis at Signalized Intersections," Ontario Ministry of Transportation and Communications, January 1982.

[7] Heti, G. et al, "Comparison of Three Arterial Traffic Control Strategies Through Field Measurements," Ontario Ministry of Transportation and Communications, August 1978.

[8] "Ontario Traffic Signal Control Equipment Specifications," Ontario Ministry of Transportation and Communications, November 1984.

[9] "Model 170 Equipment Suppliers," Ontario Ministry of Transportation and Communications, November 1984.

[10] Thomas, P.R., "General Conditions and Guidelines for the Installation of Traffic Detector Inductance Loop Sensors," Ontario Ministry of Transportation and Communications, November 1984.

[11] Heti, G. et al, "Municipal Traffic Control Systems for Ontario Municipalities -- Phase I Report," Ontario Ministry of Transportation and Communications, March 1979.

[12] Hunt, P.B., "Scoot -- A Traffic Responsive Method of Co-ordinating Signals," Great Britain Transport and Road Research Laboratory, LR No. 1014.

[13] Wallace, C.E. et al, "TRANSYT-7F User's Manual," Federal Highway Administration, December 1981.

[14] IBI Group, "Further Testing and Evaluation of the SSTOP Program," IBI Group, Toronto, Ontario, May 1980.

[15] "SSTOP User's Guide," Ontario Ministry of Transportation and Communications, September 1984.

Table 1/ Energy Consumption Estimates for Four Types of Intersection Control

	2-Way yield	2-Way stop	Traffic signal†	4-Way stop
Traffic control				
Main street	—	—	Signal	Stop signs
Side street	Yield signs	Stop signs	Signal	Stop signs
Excess fuel consumption (L/day)‡				
Main street	—	—	154.3	305.4
Side street	35.3	55.1	27.8	55.1
Total	35.3	55.1	182.1	360.5
Fuel consumption increase relative to 2-way yield				
L/day	Base	19.8	146.9	325.2
L/year	Base	7227	53 620	118 700
$/year (at 50¢/L fuel)		3614	26 810	59 350

* Traffic volume (per day): main road, 8320; side road, 1500; total, 9820.

† Traffic signal cycle length = 60 s, side street green = 18 s.

‡ Consumption estimates assume for stopping, a stop/go cycle decelerating from 50 km/h, no delay, and for yield signs, a speed reduction from 50 km/h to 18 km/h.

MINIMUM REQUIREMENTS FOR INSTALLATION OF TRAFFIC SIGNALS FOR TWO-LANE ROADWAYS

LOCATION _____ AT _____

MUNICIPALITY _____ DATE OF SURVEY _____

	WARRANT		DESCRIPTION	MINIMUM REQUIREMENT FOR TWO-LANE ROADWAYS		COMPLIANCE	
				FREE FLOW	RESTRICTED FLOW		
				OPERATING SPEED GREATER THAN OR EQUAL TO 70 km/h	OPERATING SPEED LESS THAN 70 km/h	SECTIONAL %	③ ENTIRE %
INTERSECTION	1. MINIMUM VEHICULAR VOLUME	①A	Vehicle Volume, All Approaches for Each of the Heaviest 8 Hours of an Average Day, and	480	720		
		④B	Vehicle Volume, Along Minor Streets for Each of the Same 8 Hours	120	170		
	2. DELAY TO CROSS TRAFFIC	①A	Vehicle Volume, Along Major Street for Each of the Heaviest 8 Hours of an Average Day, and	480	720		
		②B	Combined Vehicle and Pedestrian Volume Crossing the Major Street for Each of the Same 8 Hours	50	75		
	3. ACCIDENT HAZARD	A	Total Reported Accidents of Types Susceptible to Correction by a Traffic Signal, per 12 Month Period Averaged Over a 36 Month Period, and	5			
		B	Adequate Trial of Less Restrictive Remedies, Where Satisfactory Observance and Enforcement Have Failed to Reduce the Number of Accidents, and	YES ☐ NO ☐			
		C	Fulfillment of Either of the Above Warrants (Minimum Vehicular Volume or Delay to Cross Traffic) to the Extent of 80% or More.	YES ☐ NO ☐			
	4. COMBINATION WARRANT		Two or More of the Above Warrants (1, 2 or 3) Satisfied to the Extent of 80% or More.	YES ☐ NO ☐			
MID-BLOCK	5. MINIMUM PEDESTRIAN VOLUME	A	Pedestrian Volume Crossing the Major Street Average per Hour for the Heaviest 8 Hours of an Average Day, and	120	240		
		①B	Vehicle Volume Along Major Street Average Per Hour for the Same 8 Hours.	290	575		

NOTES:

① Vehicle Volume Warrants (1A), (2A) and (5B) for Roadways Having Two or More Moving Lanes in one Direction Should Be 25% Higher Than Values Given Above

② For Definition of Crossing Volume Refer to Note ④ on the Signal Warrant Analysis Form 82.03.08

③ The Lowest Sectional Percentage Governs the Entire Warrant.

④ For "T" Intersections the Values for Warrant (1B) Should Be Increased by 50%

Figure 1/ Minimum Requirements for Installation of the Traffic Signals for Two-Lane Roadways

TRAFFIC SIGNAL WARRANT ANALYSIS FORM FOR INTERSECTION CONTROL.

Minimum warrants for installation of traffic signals for roadways with two or more lanes

Major street No of lanes
Minor street

FREE FLOW CONDITIONS (RURAL) ☐
RESTRICTED FLOW CONDITIONS (URBAN) ☐

WARRANT 1 – MINIMUM VEHICULAR VOLUME

100 % SATISFIED – YES ☐ NO ☐
80 % SATISFIED – YES ☐ NO ☐

	MINIMUM REQUIREMENTS (80% SHOWN IN BRACKETS)				PERCENTAGE WARRANT HOUR ENDING									
APPROACH LANES	1		2 or MORE											
FLOW CONDITION	FREE FLOW ☐	RESTR FLOW ☐	FREE FLOW ☐	RESTR FLOW ☐										TOTAL ACROSS
A ALL APPROACHES	480	720	600	900										
	(385)	(575)	(480)	(720)										
	100% FULFILLED													
	80% FULFILLED													SECTIONAL PERCENT
	ACTUAL % IF BELOW 80% VALUE													
													TOTAL DOWN	*8*
B MINOR STREET BOTH APPROACHES	120° (95)°	170° (135)°	120° (95)°	170° (135)°										TOTAL ACROSS
	100% FULFILLED													
	80% FULFILLED													SECTIONAL PERCENT
	ACTUAL % IF BELOW 80% VALUE													
													TOTAL DOWN	*8*

*FOR 'T' INTERSECTIONS THESE VALUES SHOULD BE INCREASED BY 50%

WARRANT 2 – DELAY TO CROSS TRAFFIC

100 % SATISFIED – YES ☐ NO ☐
80 % SATISFIED – YES ☐ NO ☐

	MINIMUM REQUIREMENTS (80% SHOWN IN BRACKETS)				PERCENTAGE WARRANT HOUR ENDING									
APPROACH LANES	1		2 or MORE											
FLOW CONDITION	FREE FLOW ☐	RESTR FLOW ☐	FREE FLOW ☐	RESTR FLOW ☐										TOTAL ACROSS
A MAJOR STREET BOTH APPROACHES	480	720	600	900										
	(385)	(575)	(480)	(720)										
	100% FULFILLED													
	80% FULFILLED													SECTIONAL PERCENT
	ACTUAL % IF BELOW 80% VALUE													
													TOTAL DOWN	*8*
B TRAFFIC CROSSING MAJOR STREET	50 (40)	75 (60)	50 (40)	75 (60)										TOTAL ACROSS
	100% FULFILLED													
	80% FULFILLED													SECTIONAL PERCENT
	ACTUAL % IF BELOW 80% VALUE													
													TOTAL DOWN	*8*

Figure 2/ Traffic Signal Warrant Analysis Form for Intersection Control

WARRANT 3 - ACCIDENT EXPERIENCE

100 % SATISFIED - YES ☐ NO ☐
80 % SATISFIED - YES ☐ NO ☐

A. Reportable accidents within a 12 month period averaged over 36 consecutive months susceptible to correction by a traffic signal.		
WARRANT VALUE	AVERAGE NUMBER OF ACCIDENTS	FULFILLED
5		%
B. Adequate trial of less restrictive remedies has failed to reduce accident frequency.		100 % 0 % - Yes ☐ No ☐
C. Either Warrant 1 (Minimum Vehicular Volume) or Warrant 2 (Delay to Cross Traffic) satisfied 80% or more.		100 % 0 % - Yes ☐ No ☐

WARRANT 4 - COMBINATION WARRANT

SATISFIED - YES ☐ NO ☐

Used if no warrant satisfied 100%

REQUIREMENT	WARRANT SATISFIED 80% OR MORE	FULFILLED
Two Warrants Satisfied 80%	Warrant 1 – Minimum Vehicular Volume - Yes ☐ No ☐ Warrant 2 – Delay to Cross Traffic - Yes ☐ No ☐ Warrant 3 – Accident Experience - Yes ☐ No ☐	- Yes ☐ No ☐

CONCLUSION: TRAFFIC SIGNALS WARRANTED – YES ☐ NO ☐

WARRANT 5 – FOR MID-BLOCK SIGNAL

100 % SATISFIED - YES ☐ NO ☐

	MINIMUM REQUIREMENT					
APPROACH LANES	1		2 or MORE		TOTAL	AVERAGE
FLOW CONDITION	FREE FLOW	RESTR. FLOW	FREE FLOW	RESTR. FLOW	8 HOURS	1 HOUR
A PEDESTRIANS CROSSING MAJOR ST.	120	240	120	240		
B MAJOR STREET BOTH APROACHES	290	575	365	720		

NOTES: 1 The warrant values are based on annual average daily traffic (AADT) which approximates May and October traffic

2 For warrants 1, 2, 3 and 4, each hourly volume must exceed the minimum requirements for the warrant to be 100% satisfied

3 For warrant 5 the 8 hour average must exceed the minimum requirements for the warrant to be 100% satisfied

4 The crossing volume is defined as:

(1) Left turns from both minor street approaches
(2) The heaviest through volume from the minor street
(3) 50% of the heavier left turn movement from major street when both of the following criteria are met:
  (a) The left turn volume > 120 vph
  (b) The left turn volume plus the opposing volume > 720 vph
(4) Pedestrians crossing the major street

Figure 3/ Accident Experience Warrant

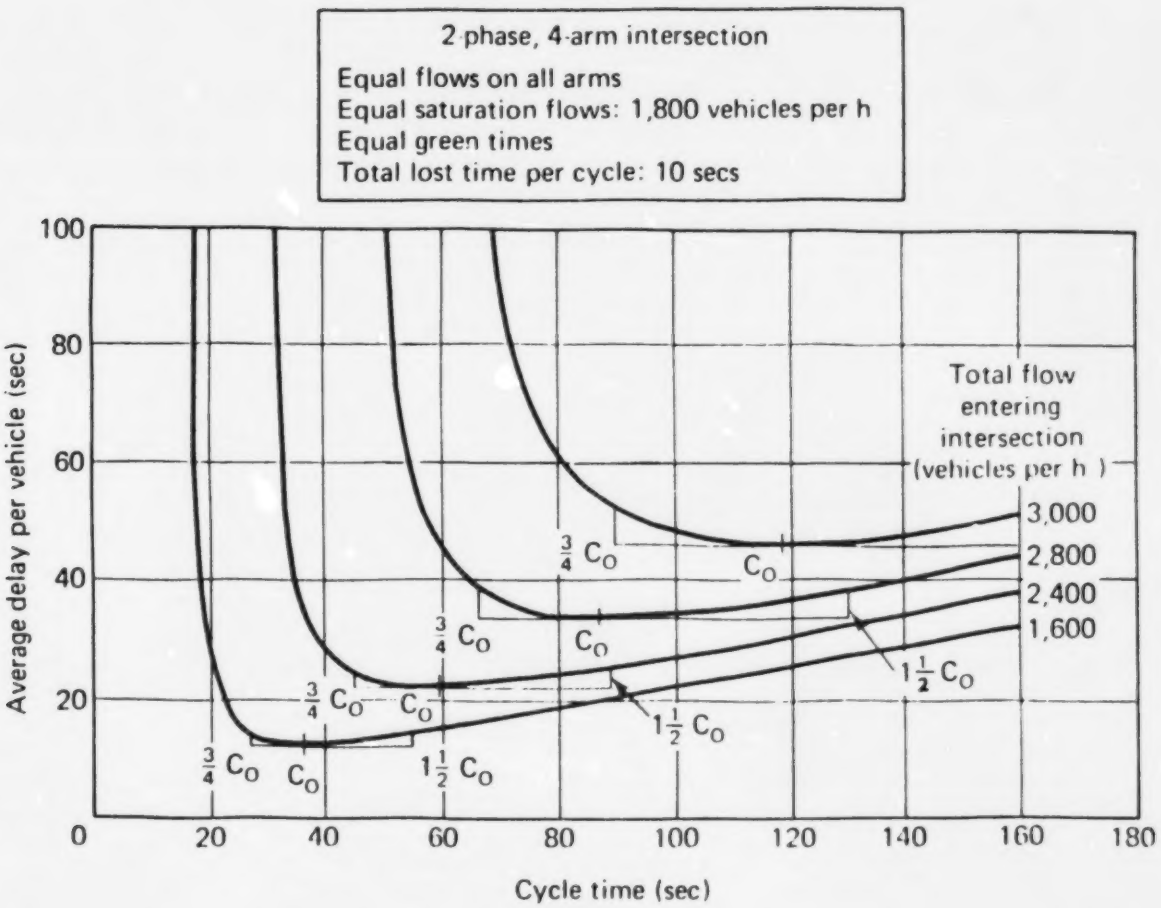


Figure 4/ Effect on Delay of Variation of Cycle Length

CYCLE: 90 SECONDS

SPLIT: 70/30 PERCENT
63/27 SECONDS

SPACING: 100 METRES

ZERO OFFSET

PROGRESSION SPEED:
500/36 = 13.9 m/sec = 50 km/h

BAND WIDTH:
27 sec. = 30%

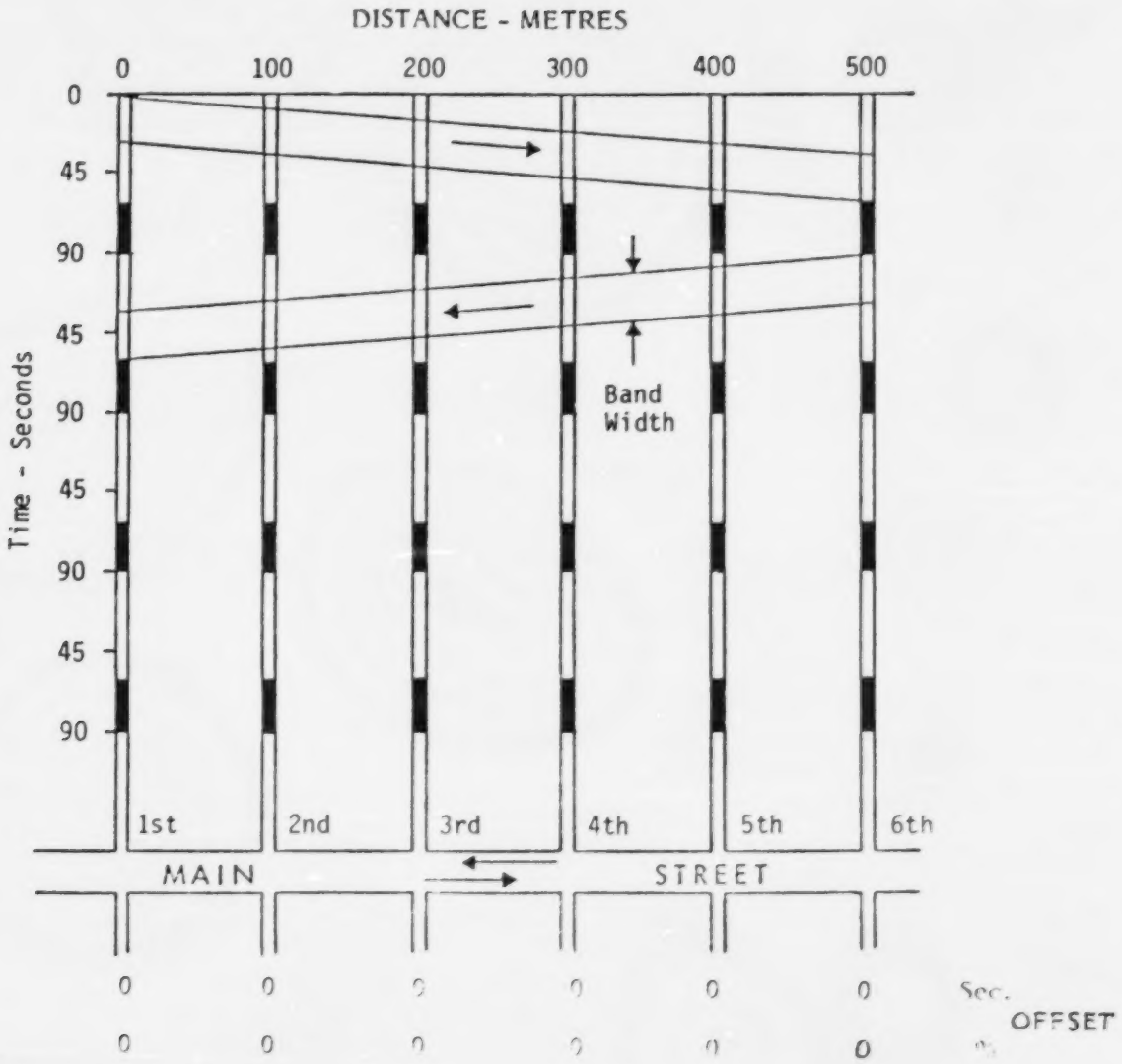


Figure 5/ Traffic Signals – Space-Time Diagram

Ministry of Transportation and Communications
Ontario

TURNING MOVEMENT STUDY

FIELD TALLY SHEET

ENVIRONMENTAL AND OPERATIONAL PLANNING BRANCH

LOCATION _____ DATE _____

_____ TIME PERIOD _____

WEATHER _____ OBSERVERS NAME _____

_____

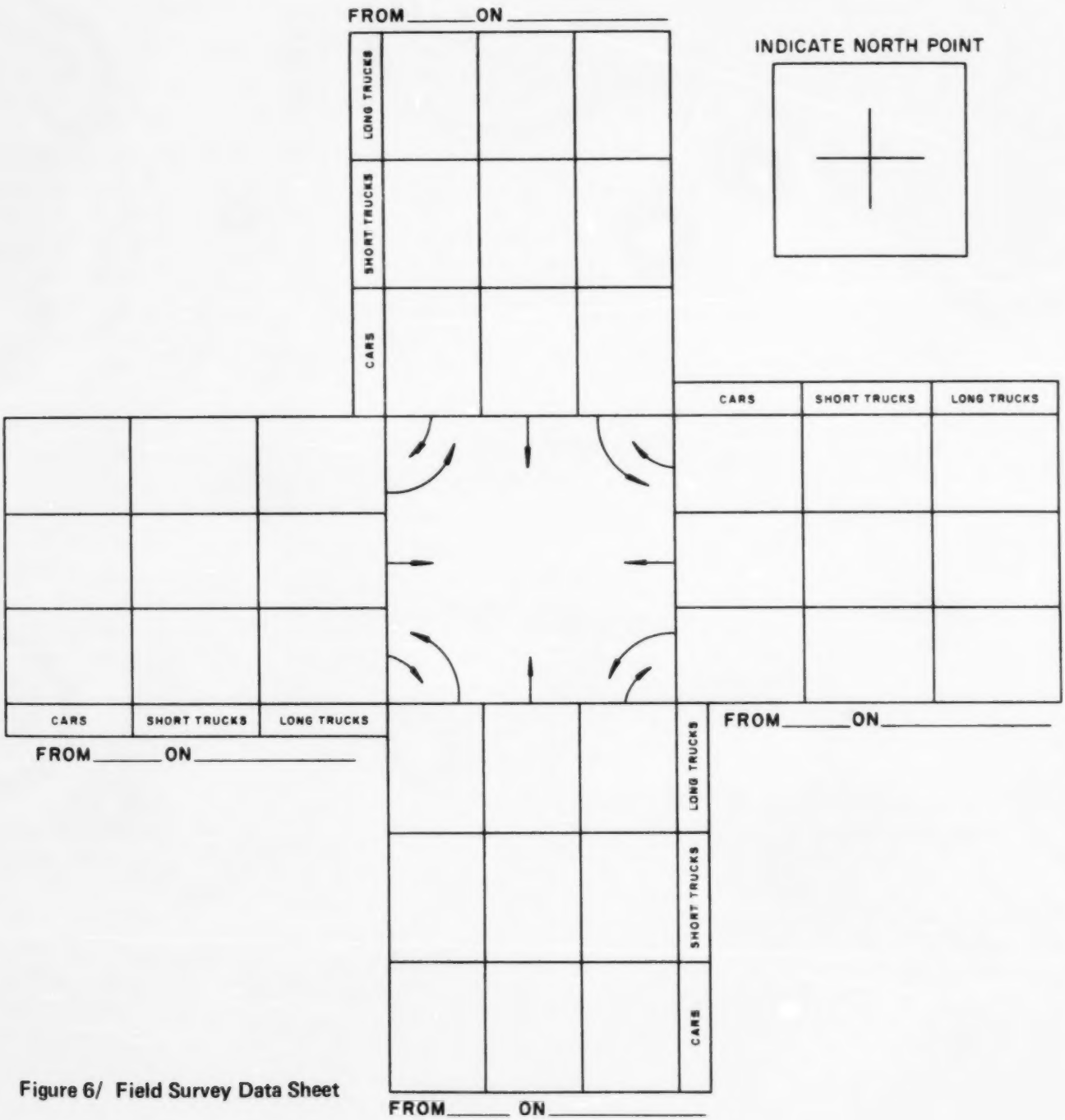
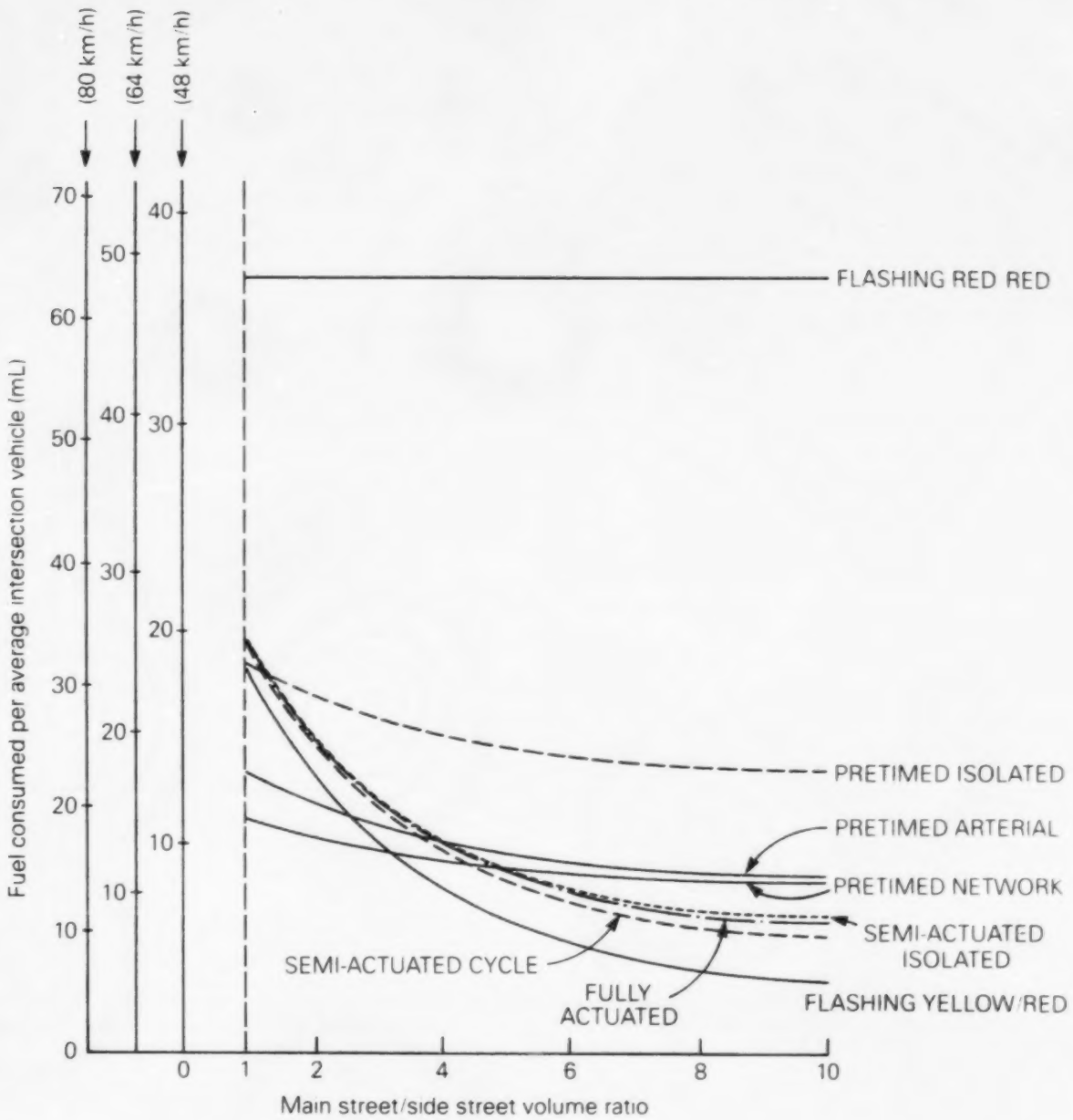


Figure 6/ Field Survey Data Sheet



SOURCE: *A Study of Clearance Intervals, Flashing Operations, and Left-Turn Phasing at Traffic Signals* Vol 1-4 U S DOT, Federal Highway Administration, Report no FHWA-RD-78-46, 1980

Note: Pretimed isolated and two semi-actuated types of control not based on field data

FLASHING RED RED, flashing red signals in both main and side streets, PRETIMED ISOLATED, fixed timed, isolated intersection, PRETIMED ARTERIAL, fixed timed, arterial system of signals, PRETIMED NETWORK, fixed timed, network system of signals, SEMI ACTUATED ISOLATED, semi-actuated, isolated intersection, FULLY ACTUATED, fully actuated, independent intersection, SEMI-ACTUATED CYCLE, semi-actuated interconnected signal with a background cycle length, FLASHING YELLOW RED, flashing red signal on the main street and yellow on the side street

Figure 7/ Average Fuel Consumption per Intersection Vehicle as a Function of Main-Street/Side-Street Volume Ratio

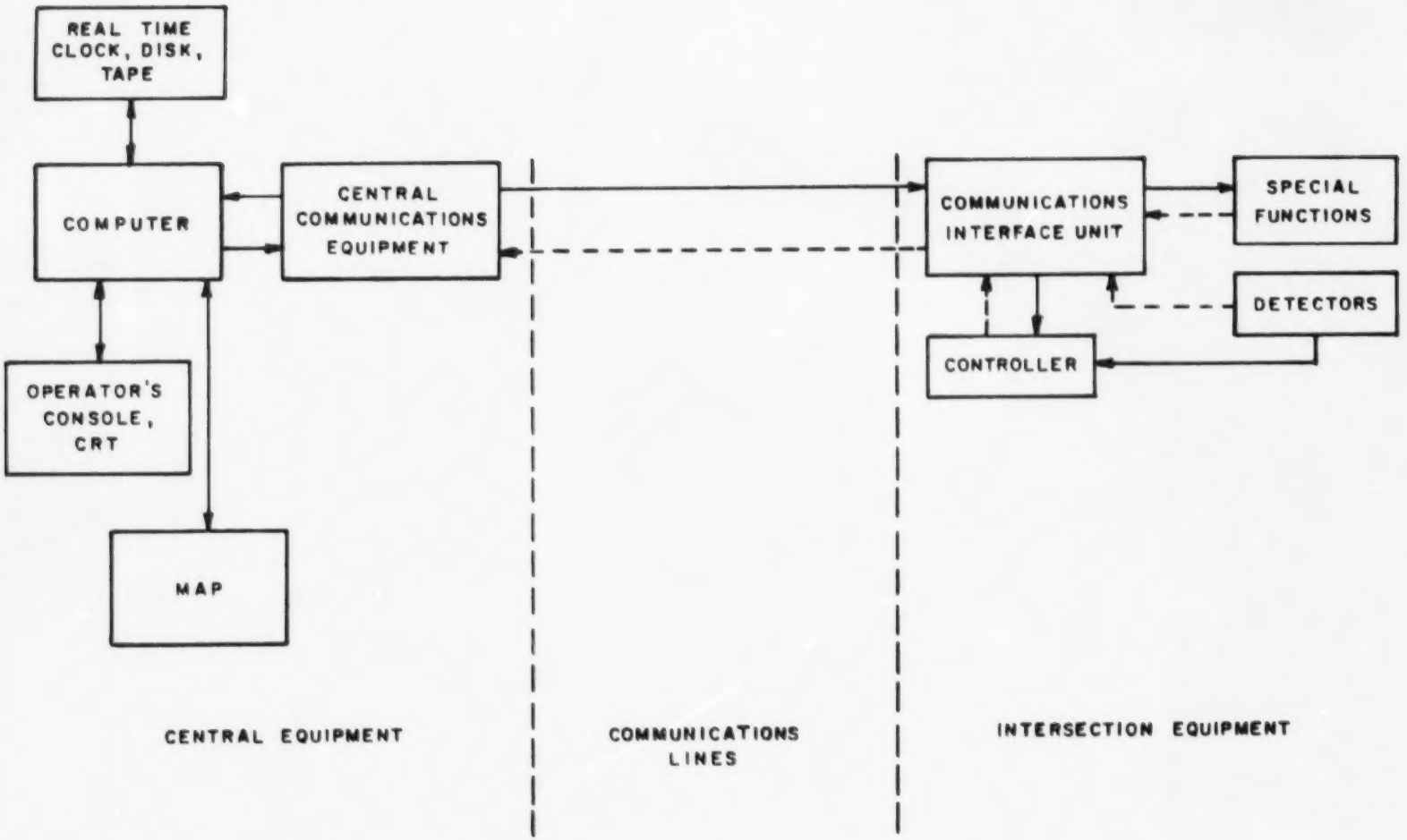


Figure 8/ Computer System Components

Ontario

Ministry of
Transportation and
Communications
Hon. Ed Fulton
Minister